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Author post-print (accepted) deposited by Coventry University's Repository

Original citation & hyperlink:
Davies, H & Bastien, C 2021, 'An approach for the crash safety assessment of smaller and lightweight vehicles', Transport Policy, vol. 105, pp. 12-21.
https://dx.doi.org/ 10.1016/j.tranpol.2021.02.009

DOI 10.1016/j.tranpol.2021.02.009
ISSN 0967-070X

Publisher: Elsevier

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DOI: 10.1016/j.tranpol.2021.02.009

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An Approach for the Crash Safety Assessment of Smaller and Lightweight Vehicles

ABSTRACT

Concerns around the externalities resulting from transport are leading to a reassessment of our mobility options. By reference to policy priorities, it is concluded that there will be an emerging demand for smaller and lighter vehicles. Within Europe these will be of the L6e and L7e category. However, the crash safety of these vehicles presents an impediment to their broader commercialisation, acceptance, and further development. The authors identify a number of concerns associated with the approaches to crash safety assessment being discussed and promoted by stakeholders. These concerns include: cascading down existing passenger vehicle (M1 category) test requirements to the L6e and L7e category would be inefficient as there is little inclination at present to develop, manufacture and market small and lightweight M1 category vehicles; subjecting the L6e and L7e category vehicles to the same crash test and test performance requirements as an M1 category passenger car would not result in comparable performance in single vehicle or vehicle-to-vehicle collisions; and vehicle use cases will differ leading to different accident patterns and questioning the efficacy of the existing M1 category test approach for these smaller and lighter vehicles. To improve the safety of lightweight vehicles would require an innovative test and assessment framework that provides benefits to consumers, producers and society. As a contribution to this framework, an approach is proposed for the assessment of crashworthiness that: responds to the immediate concerns around the safety performance in frontal collisions; aligns with the emerging capabilities of the L-category industry; and provides the consumer with a new mobility option that responds positively to key externalities associated with our use and consumption of transport. The proposed assessment is discussed and is shown to provide equivalent compartment strength to a mid-sized M1 category passenger car – thereby addressing a key concern about compartment integrity in collisions with larger and heavier vehicles.

1 INTRODUCTION

Concern around the externalities resulting from transport are leading to a reassessment of our mobility options. In addition to a ban on the sale of fossil fuelled cars being pursued by national governments[1,2,3,4,5,6], a further pathway is a move to smaller and lighter vehicles that would align with specific mission requirements e.g. single occupancy journeys in urban environments. However, there is a dichotomy. Whilst such a pathway offers the potential to reduce key externalities in relation to environment, congestion and energy dependency, there is a concern around the safety of smaller and lighter vehicles (Santucci et al., 2016; Ewert et al., 2020). At present, smaller and lighter vehicles (those that reside below the existing M1 passenger vehicle category) are assessed for crashworthiness at a lower level than for passenger cars, either as part of regulatory activity or consumer information programmes, or crashworthiness assessment is omitted entirely. This paper looks at bridging

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[1] End to the sale of new petrol and diesel vehicles to 2035 – including hybrids (UK Government, 2020)

[2] Introduce legislation to ban the sale of new fossil fuel cars from 2030 (Government of Ireland, 2020)

[3] All passenger cars and light vans sold from 2025 shall be zero-emission (Government of Norway, 2017)

[4] Committing to all new cars being zero-emissions vehicles as of 2030 (Government of the Netherlands, 2019)

[5] Objective of ending the sale of vehicles that emit greenhouse gases in 2040 (Government of France, 2017)

[6] No new petrol or diesel driven cars will be sold after 2030 (Government of Sweden, 2019).

that gap with a proposal for crashworthiness assessment of smaller and lighter vehicles that acknowledges the particular challenges unique to this vehicle class and its position in the market place. The structure of this paper is as follows. Section 2 provides a background and discusses the key externalities. Section 3 discusses existing proposed approaches to the assessment of crashworthiness for smaller and lighter vehicles and highlights a number of issues. Section 4 proposes a new approach to assessment of crash safety in frontal collisions that looks to balance the competing interests of multiple stakeholders. Section 5 and 6 provide a discussion and consideration of other crash modes, and conclusions respectively.

2 BACKGROUND

2.1 Transport Externalities

Green House Gas (GHG) emissions, urban pollution and congestion, and a dependency on fossil fuels are key problems associated with our current mobility choices.

- Emissions: The ‘Paris Agreement’ of 2015 aims to limit global temperature rise to below 1.5^{o}C through reduction in GHG emissions. Road transport, as the source of one-fifth of total CO_2 emissions from fuel combustion, has become one of the focal points (Santos and Davies, 2019).

- Pollution: Despite overall reductions in land transport pollutant emissions since the 1990s, the rate of decline has slowed in recent years leading to renewed concerns over the ability of cities to meet legal targets. In a recent study for the period 2005 to 2016, in the cities of Paris and London, almost all roadside locations exceeded the European Limit Value (ELV) for NO_2 (Font et al., 2019). Further to this, and based on trends observed between 2010 and 2016, roads in Paris will need between 4 and 20 years to attain the ELV and for London's roads this is between 2 and 193 years.

- Congestion: By 2050, there will be 2.4 billion additional urban dwellers compared with 2015. This strong urbanization process will create a substantial new demand for mobility in cities (Chen, 2017). As an example, London’s population is expected to grow 20% to 10.5 million by 2041 (TfL, 2017) with the number of trips made on existing transport infrastructure expected to rise from 26.7 million in 2015 to 32.2 million per day by 2041 (TfL, 2016). As potential to extend the road or rail network capacity is limited in urban settings, this puts additional pressures on an already strained transport system leading to an increase in congestion events.

- Energy dependency: As transport accounts for two-thirds of the European Union’s final demand for oil and petroleum products (Transport & Environment, 2016; Cambridge Econometrics, 2016), this poses a particular issue and places a constraint on the longer term viability of the transport system. Further to this, a change to alternative energy sources also poses problems, as there is expected to be an energy gap between generation and supply particularly in the renewables sector (IMechE, 2016).

Smaller and lightweight vehicles (together with cycling and walking) can contribute to removal of conventional transport modes from city centres increasing system capacity – land use is more efficient as small vehicles in general offer opportunity to expand capacity of existing infrastructure (road space, parking). It is also an argument for electro-mobility, the need to compensate for battery weight in electric vehicles means that these lightweight vehicles can cover longer distances with the same battery capacity (Davies, 2019). Electrification disrupts the dependency upon fossil fuels for transportation, whilst smaller more efficient electric vehicles reduce overall energy use and materials used in battery manufacture – a key consideration given the projected limitations in the material supply chain (Davies, 2019). Therefore, it can be stated that there is an emerging requirement – driven by environmental targets, increasing urbanization and a dependency of fossil fuels – to downsize personal transport (Box et al., 2015; Nagasaka et al., 2017; Mizuno et al., 2013). Commensurately, an expansion of the vehicle fleet within the smaller and lightweight vehicle sector can be expected.

2.2 Smaller and Lightweight Vehicles

One impediment to the broader commercialisation, acceptance, and further development of smaller and lightweight vehicles is the current regulatory fragmentation. Within Europe, the present system of classification that has been adopted for regulatory purposes is the L-category. This categorisation covers vehicle types ranging from powered two-wheelers up to the car-like heavy quadricycles termed L6e and L7e (see report MCIA, 2019). For Japan an equivalent classification contrasting to the L6e and L7e in Europe would be the ‘Kei’ or midget car – and the more recently discussed micromobility segment (Davies and Nieuwenhuis, 2017). For Korea it would be the low speed electric vehicle or light car (Honey et al., 2015). Each classification imposes different requirements in terms of vehicle size, performance, etc. In addition to creating differentiation compared to existing passenger vehicle types, these requirements often align with a domestic political agenda, for example the Korean minicar requirements differ from the Kei car requirements with the purpose of limiting imports from Japan and creating a protected market space to support domestic manufacturers (Davies and Nieuwenhuis, 2017). However, going forward, the existing system of national approvals has the potential to negatively influence the industry, because approving at a national level (potentially to different country specific requirements) may inhibit the market and would ultimately increase the costs to manufactures and consumers. Furthermore, an increase in the popularity of these vehicles would give cause for concern, as it is acknowledged that the requirements in the area of crash safety is not at the same level as for passenger cars. For example, whilst the Korean minicar and Japanese Kei car segment require assessment of crashworthiness (of varying severities), the European L6e and L7e categories and the more recent Japanese micromobility segment do not.

The decision to impose crashworthiness requirements as part of the regulatory process is a complex one and depends on a multitude of factors. The policy that informs regulation can be distilled down to casualty reduction from road traffic collisions and protection of the environment. One approach to achieving these policy objectives is imposing minimum vehicle performance requirements. This has an associated cost that must be met by the producer and recouped through vehicle sales. This raises a potential issue for smaller and lighter vehicles, given that sales are limited to their respective domestic markets (as a result of the fragmented regulatory approach). According to the European Quadricycle League, sales of Quadricycles (L6e and L7e) in EU are around 35,000 per year and the total size of the fleet is considered to be around 320,000 (Maldonado 2016, personal communication, 4th March). When this is compared to the approximately 15 million new M1 category passenger vehicles (ACEA, 2020) and 1.7 million new motorbikes (MCD, 2020), the quadricycle market is therefore relatively small.

The definition of crashworthiness requirements is also intertwined with operational limitations – for example, the imposition or restrictions on the freedoms given to the user or access to the road network. Therefore impact, in terms of safety outcomes, can be managed through a combination of vehicle, user and infrastructure (a framework). It is therefore perhaps not unsurprising that where crashworthiness assessment is omitted, in their place are restrictions on user and road access – for example, the US Low Speed Vehicle (LSV) category restricts the class of roads and the maximum speed, but does not impose crashworthiness requirements (Honey et al., 2015). Hence, whilst there are concerns regarding the crash safety provision, in particular of L6e and L7e vehicles sold in Europe, these are being managed to an extent by other actions. However, if the numbers of vehicles in the fleet were to increase in response to transport externalities, then a likely higher fatality risk[7], combined with greater intensity of use would undoubtedly refocus concerns on their crashworthiness.

3 CURRENT PROBLEMS

There is a clear conflict between the need to reduce key transport externalities on the one hand and the requirement to provide a safe transport system on the other. Initiatives to promote the broader commercialisation, acceptance, and a further development of smaller and lightweight vehicles sit at the very centre of this conflict.

> *"Critical structural shortcomings and inadequate restraint systems [for those Quadricycles evaluated] add up to unacceptably high risks of serious injury, even at moderate test speeds"*
>
> European New Car Assessment Programme (EuroNCAP, 2016)

> *"I hear NCAP implying that those who walk, cycle, ride or use a 3-wheeler must not seek a safer alternative in the quadricycle; they must continue as they are until they can afford a high emission, low mileage, congestion causing car instead"*
>
> Rajiv Bajaj (Bajaj, 2016)

The question is, are smaller and lightweight vehicles to be viewed as a direct replacement of the passenger car and used accordingly (reinforcing the valid concerns expressed by

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[7] The limited available data for the EU indicates that for quadricycles the death risk per unit distance driven is higher than that of passenger cars, in certain cases between 10 and 14 times higher (Robinson et al., 2009). However, the picture is far from clear. It is not always possible to disaggregated by quadricycle type, making the safety risk of different types of quadricycle (ride-on as opposed to ride-in) difficult to determine. Further, the different use cases may alter exposure to events that have the potential to cause harm – a study that considered fatality risk per rate per million vehicles (as opposed to distance travelled) showed that fatality risk for the occupant of the light vehicle to be lower than for the occupant of the passenger car (Edwards et al., 2014).

EuroNCAP) or perhaps as a new mobility offer positioned midway between existing offers (reducing the key externalities associated with the present transport offer)? Should they perform all expected vehicle missions, or would they occupy a niche e.g. single occupancy short distance journeys in urban areas? These are fundamental questions, as the type of use case informs our requirements and expectations in terms of crashworthiness.

3.1 Regulatory framework

In responding to concerns around the crashworthiness of smaller and lighter vehicles, the position that is often described is concerned with the adoption of mature regulatory frameworks. This would align with the expectation that they provide the same mobility offer and are used as such. However, in many respects this would duplicate an existing option open to manufacturers – the ability to type approve to M1 passenger car category. As there is no lower mass limited for the M1 category, a vehicle conforming to the same overall packaging and drivetrain limitations as required by L7e could be type approved as either a quadricycle or a passenger car. This has been done previously, but only by niche manufacturers and with limited volumes (Figure 1). As there is little inclination at present to develop, manufacture and market small and lightweight M1 vehicles in any significant quantities, then an opportunity for a modal shift may be missed. Such an approach, to cascade down regulatory requirements from M1 to the category below, can therefore be viewed as inefficient.

Passenger Car M1 (Only driving licence B)
Minimum age EU 18 years

Quadricycle L7e (Driving licence B or B1)
Minimum age EU 16 years

Figure 1: Same vehicle model can be certified as M1 or L7e

3.2 Costs

There is also a cost element to consider in extending the existing M1 passenger car test to the L6e and L7e categories. A report by the UK Transport Research Laboratory quoted that the cost of aligning the quadricycle (L7e and possibly L6e) requirements with M1 passenger vehicles was in the region of €700,000 (Davies, 2016). This cost would be spread over a smaller sales base. As a comparison, market leader Aixam-Mega annual production volume (across all L-category models) reached a peak of 15,500 units in 2007 (Aixam, 2012), whilst a comparable M1 model, in this case the similar sized, but heavier, Smart Fortwo (see Figure 2), achieved a peak annual sales volume in the EU market alone of over 100,000 units (Carsalesbase, 2020). Nevertheless, to date, several of the French quadricycle manufacturers, including the market leaders Aixam-Mega and Ligier-Microcar have voluntarily built their vehicles taking into account crashworthiness requirements of the type applied to M1 passenger vehicles in order to avoid losing sales through adverse publicity around this issue. In addition, some have started offering airbags. Although airbags are not compulsory even on M1 vehicles in the EU, they have become an industry standard and having thus become commodified, have become affordable for such smaller manufacturers. Such initiatives by the market leaders may, however, not be feasible for some of their smaller competitors (K Lindsay 2016, personal conversation, 12th February).

M1 passenger car
Daimler Smart for 2
2 seats
2.70 m long

L6e light quadricycle
Aixam City
2 seats
2.72 m long

Figure 2: Comparison Smart Fortwo (M1) and Aixam City (L6e)

3.3 Demands

The current suite of crash tests developed for the M1 passenger car are predicated on accident data and its analysis i.e. the assessment of crashworthiness has evolved based on an understanding of existing accident type/frequency and accident severity. With the introduction of greater numbers of smaller and lighter vehicles into the fleet, the key is to first understand how this would change accident type/frequency and second to understand how this would change accident severity.

With an increase in the number of smaller and lighter vehicles of the L6e and L7e category, the type of accident and the occurrence is likely to change. Whilst historically in Europe (e.g. France) quadricycles were used for the same purpose as passenger cars, the literature now strongly indicates their use as an urban mobility solution (Santucci, 2016; Ewert et al., 2020). This will likely lead to lower circulatory speeds cf. passenger cars. As a consequence, this will lead to a change in the accident distribution, with more injury accidents at lower circulatory speeds relative to higher speeds and hence a similar shift in casualty distribution (note this is referring to distribution of casualties and not actual numbers – which may fall overall due to lower circulatory speeds). This observation is supported by accident analysis performed in Japan where the Kei car segment forms a larger part of the vehicle fleet (Figure 3).

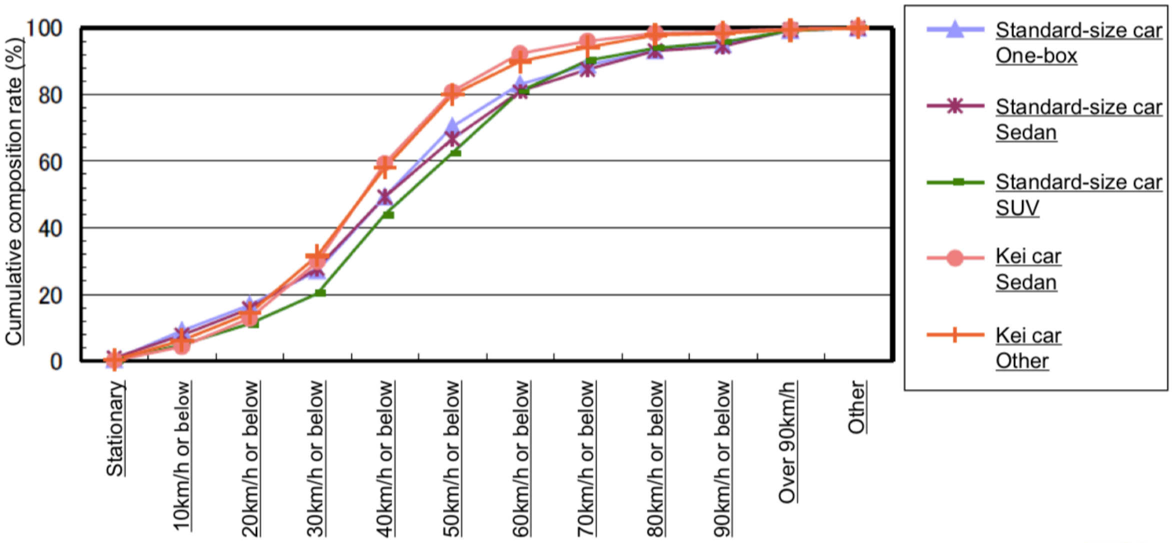

Figure 3: Danger recognition speed[8] for singe vehicle collision showing that the speed at which 50% of accidents for the Kei car occur is 5 km/h less than for the standard [passenger] car (UNECE, 2012).

It is the combination of accident distribution and severity that will determine where the potential benefits are to be realised – and to deliver upon policy objectives. Whilst additional research will be needed to investigate the development of accident patterns of the smaller and lighter vehicles as they become more prevalent in vehicle fleets, in the short to medium term, even if there was to be significant growth in the number of L6e and L7e vehicles, they would represent only a small proportion of the overall fleet. The inference, therefore, is that in an accident, the L6e or L7e vehicle would likely impact vehicles that are heavier and bigger. This mismatch between different vehicles within the same fleet that will be brought about by this downsizing is the pressing problem – putting the occupant of the smaller and lighter vehicle at a higher risk of injury compared to the occupant of the larger and heavier collision partner. Again, this observation is supported by accident analysis performed in Japan where the Kei car segment forms a larger part of the vehicle fleet. National accident data showed that the probability of fatal injury to occupants in Kei cars was comparable to that of other size passenger cars when considered across all accident types. However, in car-to-car collisions, the injury risks to occupants were higher for Kei cars as compared to larger size cars (Figure 4).

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[8] Danger recognition speed is the driving speed of the vehicle at which the party of an accident perceives the other party before it is hit and recognizes the danger of an accident (ITARDA, 2020).

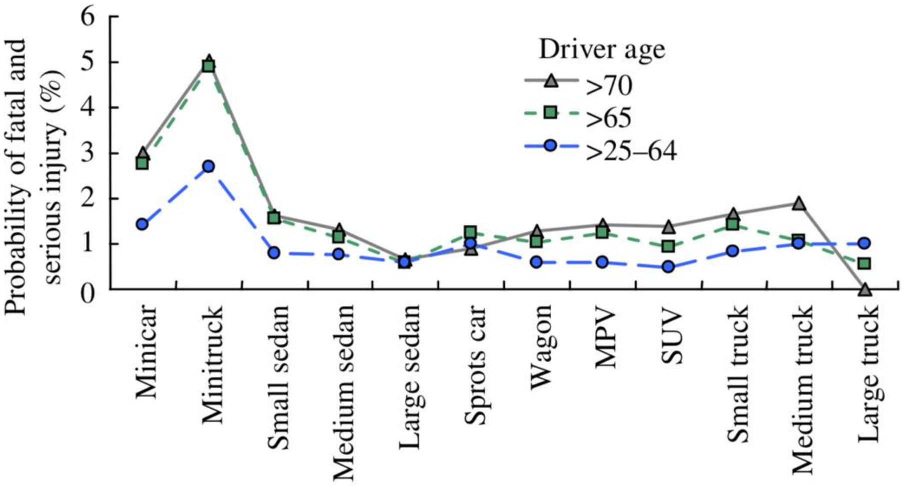

Figure 4: The probability of injuries to drivers (according to age group) for different vehicle types in vehicle-to-vehicle collisions – the minicar and minitruck refer to the Kei classification (from Mizuno et al., 2013)

3.4 Performance

In the assessment of the crashworthiness performance of lighter and smaller vehicles, a number of test procedures are currently in play. Depending on the target market, these can range from regulatory to consumer tests. For example, the popular Kei car segment in Japan has long since adopted the same crashworthiness testing approach as for passenger cars (Hitosugi and Matsu, 2015) – the market for Kei cars being larger than in Europe due to political considerations and hence the costs associated with compliance can be recouped across a significantly larger sales volume. In Europe, recognising the growing importance of this sector, the consumer testing programme EuroNCAP has developed its own crashworthiness assessment programme (EuroNCAP, 2014). Both approaches, Japan for the Kei car and EuroNCAP, take a fixed deformable barrier test as the foundation for their assessment, mirroring in principle, if not exactly replicating in detail, the discussion around adoption of existing regulatory test approaches used in Europe for M1 passenger cars for the European L-category (L6e and L7e).

3.4.1 Offset Deformable Barrier (56 km/h regulatory or 64 km/h consumer information)

The current approach to the assessment of M1 vehicles, as defined by the United National Economic Commission for Europe (UNECE) Regulation 94, is for an impact against a deformable barrier that engages 40% of the frontal width of the vehicle (UNECE, 2017). This has been adopted based on the fact that accident studies have shown that in comparison to fixed impacts with a rigid barrier, the majority of serious and fatal injuries occur when the subject vehicle impacts a partner vehicle with a partial overlap. However, whilst, the UNECE R94 test is a rigorous assessment of the capability of the vehicle frontal structure to absorb the crash energy, it also has limitations. Assessment is by means of measurements take from anthropometric test devices seated in the driver and passenger seats. These measurements are indirectly related to the acceleration experienced by the occupant and hence the acceleration of the vehicle structure. As vehicle structures perform other functions, in addition to crash, it is prudent to limit the crush length to that required to control acceleration. This defines a minimum crush distance that is mass independent to large extent (Figure 5).

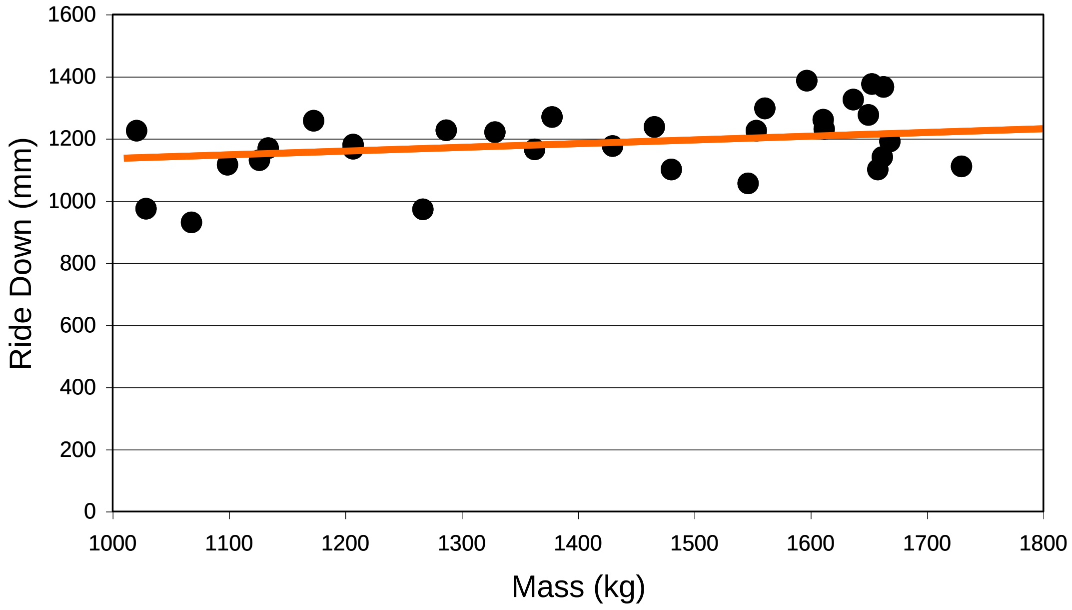

Figure 5: Vehicle ride down distance with vehicle mass measured in a 64 km/h offset deformable barrier test configuration. Note that the ride-down includes a barrier depth of 540 mm (adapted from Edwards et al., 2003)

If the vehicle front structure is approximated to a progressive spring (the force level increases progressively as the vehicle is deformed - as shown in Edwards et al., 2003) then changes in input energy due to differences in mass are accommodated by a change in the force (as displacement is fixed). Hence, the variation in vehicle mass (or crash energy) is accommodated by variation in frontal force level – the higher the mass, and hence crash energy, the higher the force level (Figure 6).

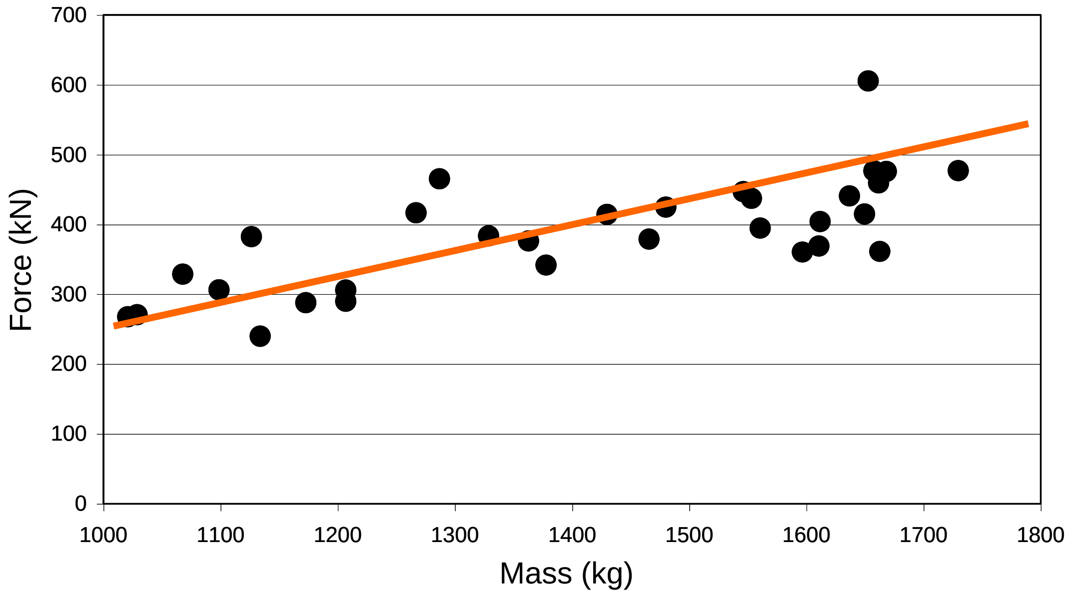

Figure 6: Frontal force level at maximum deformation with change in vehicle mass measured in a 64 km/h offset deformable barrier test configuration (adapted from Edwards et al., 2003)

This has implications for vehicle-to-vehicle impacts where the frontal force level is different between the collision partners – the vehicle with the lower force level being unable to deform the partner vehicle at the higher force levels required and leading to over-crushing of the vehicle with the lower force level. This has been accommodated for, to an extent, by accidentology showing that the majority of serious injuries occur in vehicle-to-vehicle accidents with mass ratios of 1.6 or less due to a homogeneity across the vehicle fleet – and impacts with mass ratios of 1.6 or less were shown to be survivable with appropriate safety equipment designs (Thomson, 2007). With smaller and lighter vehicles of the L6e and L7e category, the concern would be that with lower numbers circulating in the fleet, even with aggressive approaches to growth, if these vehicles experience impacts with partner vehicles, then statistically they will be existing passenger cars and the mass ratio would be significantly higher than the 1.6 quoted previously. This would exacerbate the problem of force matching and lead to worse outcomes for the smaller vehicle.

In addition to the force matching problem outlined previously, there is the further problem of mass incompatibility and the impact this has upon vehicle accelerations. Whilst the UNECE R94 test is predicated on minimising injury through controlling acceleration, in a vehicle-to-vehicle impact, the lighter vehicle will undergo a higher change in velocity than a heavier collision partner due to conservation of momentum (for a collision between objects of dissimilar mass conservation of momentum dictates that the change in the velocity of the lighter object will be greater than that of the heavier object), but both vehicles experience the same impact event i.e. the time is the same. Hence the lighter of the two collisions partners undergoes a higher acceleration – leading to a higher injury risk. Indeed, accident studies in Japan related to the Kei car have observed instances of seat belt failure for the Kei car in vehicle-to-vehicle collisions were there was significant mass incompatibility (Oga et al., 2013). This raises further questions regarding the validity of the present crash test assessment for smaller and lighter – as Kei cars presently are assessed using this approach.

Finally, it needs to be recognised that the offset test configuration (as used in UNECE R94) is an approximation of an existing accident distribution, in this case it is a vehicle-to-vehicle impact with a distribution that is centred on a 50 % overlap and a closing speed of 100 km/h (each vehicle traveling at 50 km/h). The difference between 40 % overlap in the test and the 50 % overlap in the vehicle-to-vehicle impact is that the deformable barrier in the crash test has uniform stiffness cross its width and a car does not – the 10 % difference found to be an appropriate correction factor (Lowne, 1994). The difference between the 56 km/h test speed and the 50 km/h collision speed accounts for the energy absorbed through crush of the deformable barrier face – this energy absorption capability not being available in the vehicle-to-vehicle collision (or in a single vehicle collisions with a rigid object e.g. bridge parapet). The relationship between the test speed and the collision speed (in an accident) is given by (derived from Berg et al., 1998):

$$EES = \sqrt{v^2 - \frac{2 * E_{ODB}}{m}}$$

Equation 1

Where: v is the test speed, EES is the Equivalent Energy Speed (or collision speed), m is the vehicle mass and E_{ODB} is the energy absorbed by the barrier face (referred to within the crash test community as the Offset Deformable Barrier or ODB).

Based on the premise that there is a limited variation in passenger car vehicle width and that crush strength of the barrier face is a magnitude lower than that of the vehicle, then this yields similar barrier crush profiles and hence energy absorption by the barrier face, irrespective of the vehicle that is being tested. Based on published results (Lowne, 1994) that show a 56 km/h test against a deformable barrier face as equivalent to a 50 km/h collision for a typical M1 vehicle (approx. 1500kg) then a value for E_{ODB} (the energy absorbed by the deformable barrier face) would be in the region of 36 kJ. Hence, using this 36 kJ value and a test speed of 56 km/h, a curve that shows the relationship between mass and EES is generated (see Figure 7 and refer to the curve labelled 'fixed vehicle width 1.8m'). The would give an EES for the 450 kg car of 33 km/h – representing a significant reduction in the self-protection level compared to M1 passenger vehicles. However, for lighter vehicles it need to be acknowledged that the width is generally less than for M1 passenger cars[9]. The reduction in width of the vehicle reduces the overlap with the barrier face and reduces the amount of energy absorbed by the barrier face. The EES curve representing the narrower L-category is shown in Figure 7 as 'fixed vehicle width 1.25m'. Based on this curve the EES for a 450 kg vehicle would be as low as 42 km/h. Hence, and although an increase from the previous 33 km/h, the self-protection for an L6e or L7e vehicle would still be less than for a M1 passenger car (EES 50 km/h), even though it is subject to the same test and subject to the same assessment (injury criteria). This is a significant limitation of this test approach.

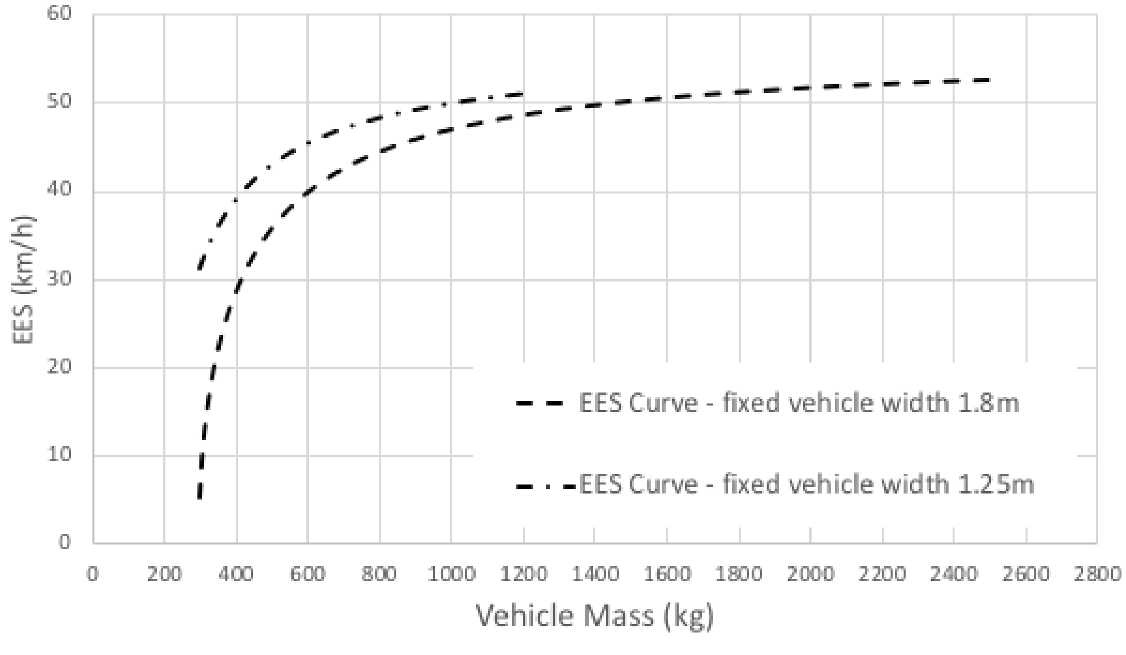

Figure 7: Change in EES with vehicle mass for test speed 56 km/h. The dashed lines represent EES for a fixed vehicle width (1.8m is the typical width for an M1 passenger car, 1.25m is the typical width for a L6e or L7e category vehicle).

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[9] Typical mid-sized M1 passenger vehicle width 1.8 m compared to around 1.25 m for L6e or L7e.

3.4.2 Full Width Deformable Barrier (50 km/h consumer information)

To respond to the limitations identified in the previous section, there have been approaches to test lightweight vehicles using full width tests (FWTs). The EuroNCAP consumer testing programme has developed test protocols using full width impact tests for both passenger cars (M1) and those that fall under the L-category (L6e and L7e) (EuroNCAP, 2014). The passenger car test impacts the vehicle against a rigid wall, whilst the L-category uses a deformable barrier face between the impacting vehicle and the rigid wall. The purpose of these tests has been primarily to assess the restraint systems as full engagement of the vehicle front structure raises the force level and hence the acceleration experienced by the passenger compartment of the vehicle structure – hence placing a greater emphasis on the seatbelt anchorage strength requirements. This has been perceived as advantageous for lighter-weight vehicles as the reduced vehicle width has led crash safety experts to believe that in a vehicle-to-vehicle impact a greater proportion of the vehicle width would be engaged, although there is limited accident data to confirm if this would indeed be the case.

The full width rigid barrier test is beneficial for the smaller and lighter vehicles in terms of assessing the performance of the restrain system – as the system must respond to similar input irrespective of the vehicle mass. The addition of the deformable barrier face exercises the ability of the front structure to respond to lower crash loads (the deformable barrier face limits the initial accelerations at the front of the vehicle structure) and hence the ability to absorb impact energy in accidents other than those with rigid structures – the addition of a deformable barrier face does however lead to a slight lowering of the impact severity for a lighter vehicle, but not to the same extent as that observed for the ODB. The limitation of this approach is that, as the assessment is based on injury outcome, the test converges to a fixed ride down distance (to achieve a positive injury outcome a minimum distance is required), but given that these are small vehicles, the inclination to extend front crash structure beyond this minimum is limited. As the input energy is fixed (and part of that energy is absorbed in crush of the barrier face[10]), this lead to a cap on the peak force level which would be less than for the opponent vehicle. In the case that the opponent is a heavier M1 passenger vehicle or if the collision was offset hence reducing the width of the front structure engaged in a collision there would be a heighted risk of compartment collapse.

Summary and concerns:

- Cascading down M1 test requirements to the L-category would be inefficient as there is little inclination at present to develop, manufacture and market small and lightweight M1 vehicles
- Fragmented system of vehicle classification limits sales volume and opportunity to amortise compliance costs leading to higher individual vehicle costs and limiting market potential
- L-category vehicles will change the casualty distribution, with more frequent injury accidents at lower circulatory speeds relative to higher speeds and hence a similar shift in casualty distribution
- L-category vehicles will change the casualty severity, with an increase in mass difference between collision partners leading to higher injury risk for the occupant of the smaller vehicle
- Subjecting the L-category vehicle to the same crash test as an M1 passenger car would not result in comparable performance to a M1 vehicle in single vehicle or vehicle-to-vehicle collisions
- Subjecting the L-category vehicle to a full width test assesses restraint system performance, but not compartment integrity which is a prerequisite for reducing injury in collisions with heavier collision partners

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[10] Based on vehicle frontal area and barrier crush strength this has been estimated at around 18kJ

4 Proposed Approach

In the previous discussion, the requirements leading to improved safety are compartment integrity and control over acceleration. Whilst both are acknowledged as leading to improved vehicle performance there is an identifiable dependency – without compartment integrity to ensure a survival space, looking to control acceleration would have limited influence. The limitation of those test procedures being proposed or discussed by the stakeholder community are that compartment integrity is ensured only at a lower impact severity – in the case of single vehicle collisions – or is not at the same level as the partner vehicle – where that partner vehicle has the greater mass. Therefore the critical first step is assessing compartment integrity. This would be followed by strategies that would minimise acceleration related injuries in relation to the evolving accident picture of L6e and L7e category vehicles.

There is an established dependency between force and deflection, and between force and energy:

$$Force = f\ (Energy; Deflection)$$

Equation 2

If the assessment is based on injury outcome, then this in turn places a limitation on the acceleration. For an impact with a fixed barrier the initial velocity and final velocity are fixed and hence acceleration is a function of displacement – the same limitation as applies to acceleration will therefore also apply to deflection. Hence, the dependency becomes:

$$Force = f\ (Energy)$$

Equation 3

To increase the force level therefore requires an increase in the system energy. As the test vehicle mass is fixed this increase in energy would need to come from an increase in the test speed. A problem with this is that an increase in impact velocity may lead to unrealistic structural failure that is not representative of a vehicle collision (due to the combination of strain rate dependency and the change to the stress wave that travels through the structure). As stress is proportional to impact velocity, the structure will be unfairly stressed with any increase of the initial impact velocity:

$$\sigma \propto \sqrt{\frac{E}{\rho}} \cdot v$$

Equation 4

Where σ is the stress, E the Youngs Modulus, ρ the material density and v the impact velocity respectively.

A further approach to increasing the system energy would be to look at the collision object. If the collision object was to be mobile and have a velocity of its own then the system energy would be increased. If the energy absorption of this 'mobile barrier' was less than the additional energy introduced to the system then this would achieve the previous requirement

– the difference between the energy introduced to the system pre-impact and the energy absorbed by the barrier post-impact would need to be absorbed by the test vehicle, hence requiring that the test vehicle force level is raised. Note, it would be desirable for the mobile barrier face to deform in order to load the vehicle structure in a similar manner to that experienced in a vehicle-to-vehicle collision – an opposing vehicle structure is not rigid, but is able to deform. The open questions are: how much energy to introduce; in reaching that energy, what should be the respective contribution of the mass and velocity of the mobile barrier; and what proportion of that energy should the barrier absorb? The following provides a case study with the objective of achieving a frontal force level comparable to a mid-sized M1 passenger vehicle.

For frontal impact, it is proposed to perform a compatibility test. This compatibility test would be performed by colliding the L-category vehicle against a 950 kg Mobile Deformable Barrier (MDB) at a closing speed of 100 km/h (as per UNECE R94 referred to previously – each collision partner travelling at 50 km/h) and an overlap of 50%. This 950 kg deformable barrier would be the standard side impact crash test barrier used in side impact test (UNECE R95). This has some major advantages:

- The barrier already exists and will add no extra cost of development for an L-category barrier
- The barrier instrumentation exists and is well understood
- The impact velocity is within the range of the crash test barrier calibration

This proposed method allows a quick implementation to test L-category vehicles. As the focus of the test is based on the vehicle structural integrity, the crash test dummy in the L-category vehicle will not be instrumented: only its inertial properties would be used. The key (positive) result is that the compartment force for a 450 kg vehicle in the proposed test would be in the same region as 1300-1500 kg cars as measured in Offset Deformable Barrier (ODB) frontal impact test. This is based on the following assessments:

Existing ODB Test (56 km/h)

- Input (crash) energy is 55kJ (car is 450 kg)
- Crash energy of 55 kJ is split 30 kJ for the car and 25 kJ for the barrier face
- In an ODB test the vehicle crush distance is approximated as 0.5 m (taken from Edwards, 2000)
- As force increases linearly with deformation the compartment force would be 120 kN (30*2/0.5)

Hence, compartment force for a 450 kg vehicle in a 56km/h ODB test would be approximately 120 kN – this would lead to concern about compartment integrity in a high mass ratio vehicle-to-vehicle collision.

EuroNCAP Full Width Test (50 km/h) having rigid barrier faced with deformable honeycomb

- Input (crash) energy is 43kJ (car is 450 kg)
- Crash energy of 43 kJ is split 25 kJ for the car and 18 kJ for the barrier face
- Taking the vehicle crush distance as 0.5 m (as for ODB test and to meet injury criteria)
- As force increases linearly with deformation the peak force would be 100 kN (25*2/0.5)

Hence, peak force for a 450 kg vehicle in a 50km/h FWT test would be approximately 100 kN – this would lead to concern about compartment integrity in a high mass ratio vehicle-to-vehicle collision, especially if there was to be a partial overlap (a partial overlap would engage less of the front structure and the force required to collapse the compartment would be less).

Proposed Compatibility Test (closing speed 100 km/h comprising 50 km/h test car and 50 km/h MDB)

- Input (crash) energy 135 kJ – split 92 kJ for the MDB (950 kg) and 43 kJ for the car (450 kg)
- Energy absorbed by barrier 30 kJ (based on stiffness and crush profile)
- Conservation of momentum gives post impact 4.96 ms^{-1} with a combined mass 1400 kg
- System Post impact energy of 17 kJ ($0.5*1400*4.96^2 = 17221$ J = 17 kJ)
- Energy absorbed by car 88 kJ (by subtracting barrier and post impact energies from crash energy)
- Taking the vehicle crush distance as 0.5 m (requirement from ODB test)
- As force increases linearly with deformation the compartment force would be 352 kN (88*2/0.5)

Hence, compartment force for a 450 kg vehicle in proposed test would be 352 kN – and is in the same region as for 1300-1500 kg cars in a 56 km/h ODB test (Edwards, 2000), therefore ensuring compartment integrity in collisions with a higher mass collision partner.

Compliance requirements can also be simplified and hence limit cost – structural strength is simply a combination of the material and the geometry and the performance will be based on intrusion according to the criteria established as part of the existing fixed barrier tests (UNECE 2017; EuroNCAP 2019). For example, these include limits on steering column displacement; graduated penalty based on A-pillar displacement; penalty applied for footwell rupture; pedal blocking; etc. These are well established mechanisms for assessing safety performance of the structure and can be applied directly to the proposed test procedure with knowledge that they deliver improved performance.

The engineering development required to meet the test requirement is significantly reduced compared to the current UNECE R94 test that requires measurements from an anthropometric test device in additional to structural requirements. This is critical for a market sector where costs have to be amortised over significantly lower number of vehicles.

5 Discussion

Safety is an emotive subject. The drive towards the downsizing of our personal transport raises many questions as regards to safety. As regulators, not only is there a requirement to respond to the question of safety, but also respond in a way that provides benefits to each and all stakeholders. Pursuing a strategy of applying existing solutions developed for a market sector that is different in structure and purpose to the lightweight vehicle sector will provide a benefit, but at what cost? The L-category vehicles that are discussed in this paper are different to current M1 category vehicles. Firstly, whilst M1 passenger vehicles mix with other M1 passenger vehicles in operation, the L-category vehicle will primarily mix, at least in the short to medium term, with non L-category vehicles. The focus should therefore be on how the vehicle performs when in conflict with these other vehicle types.

Based on the present sales figures, lightweight vehicles are going to be in the minority and the collision partner in an accident involving another vehicle is more than likely to be an M1 passenger car. In frontal impacts, the priority is therefore to ensure compartment integrity. In this respect the existing UNECE test as applied to M1 passenger cars is not suitable. A test involving an MDB has been proposed. Based on the figures used in this paper the MDB test would drive up passenger compartment strength for a lightweight vehicle to the equivalent of a passenger car in the 1200-1500 kg range. This improvement in compartment strength is also accompanied by more rigorous performance testing of restraint systems in L6 and L7 category vehicles – addressing the issue noted previously in accidents with the Kei car where the instances of seat belt failure observed in the accident scene was not picked up in testing using the fixed barrier approach.

Proposal: Frontal Impact (vehicle-to-vehicle) > offset MDB > assessment of structural integrity (and seat belt anchorage)

In terms of single vehicle accidents, the proposed compatibility test will increase the structural stiffness. This may cause non-contact induced injuries in accidents in which the energy levels are not as high, but the accelerations are severe. These would likely be single vehicle accidents – also vehicle-to-vehicle where the mass ratio between collision partners is not significant. The proposed approach is to complement the MDB test with a fixed ODB test approach – for example conforming to UNECE R94. This will look to tailor the force-deflection characteristics to achieve a balanced outcome across the two tests (MDB and ODB) in a similar way to the combination of FWT and ODB achieves in assessment of M1 passenger cars. This would be optional and hence targeted at manufactures with larger production numbers. As an alternative, the assistive technologies that have become commoditised on M1 vehicles should be encouraged to be fitted to the L-category vehicles.

Proposal: Frontal Impact (Single Vehicle) > option of ODB or assistive technologies

In side impacts the problem is less acute as the problem for L6 and L7 vehicles is closer in concept to that of the M1 passenger car – the concern is to ensure that contact between the intruding structure and the occupant is appropriately managed through control of the deformation pattern. To minimise costs a proposal is to use intrusion as a surrogate for occupant injury. This removes the requirement for an anthropometric test device and the resulting costly fine tuning. Intrusion has been shown to be an appropriate surrogate for injury outcome in vehicle impacts – for example the proposal put forward by the IIHS (IIHS, 2017).

Proposal: Side Impact > side MDB > assessment of intrusion

Whilst the frontal and side impact proposals ensure compartment integrity, there are other crash configurations that also require attention. Roll over (in terms of frequency and injury represents a low contribution relative to front and side, but possibly higher for lightweight vehicles due to smaller footprint cf. vehicle height) would require roof crush testing and this could follow the example of FMVSS, but with quasi static loading initially (for example following IIHS, 2016) before moving to dynamic is accident analysis shows that it is required.

Proposal: Roll Over > Quasi static roof crush > intrusion assessment

For vulnerable road users the picture is less clear. The packaging requirements mean that the present UNECE requirements are more challenging. The introduction of driver assist and active measures are proposed. This is achievable in the medium to long term as these systems become commoditised due to their wider application in M1 passenger cars.

Proposal: VRU > assistive technologies

The Future?

Transforming the individual vehicle we drive today requires several changes in a holistic sense: electric variants; the creation of an environment whereby smaller more efficient vehicles can provide a benefit; changing society to see the value of the most appropriate vehicle for a particular journey; supporting suppliers to invest in the development and manufacture of alternative smaller vehicles. With a such a complex system the interventions must be planned and must be co-ordinated in order to support market acceptance. The development of the above crashworthiness proposals forms the a basis for future work in this area, but in doing so, this will need to be supported by additional research in areas that include accident analysis, behavioural sciences and technology development. From a behavioural perspective, there is a requirement to understand if smaller and lighter vehicles will perform the same vehicle missions as existing passenger car or would they occupy a niche e.g. single occupancy short distance journeys in urban areas? These are fundamental research questions, as the type of use case informs our requirements and expectations in terms of crashworthiness. In moving to smaller and lighter vehicles, the collision configuration and the evolution of the collision configuration resulting from changes in vehicle type and technology availability – as well as user behaviour – will need to be understood and tracked. The research question is to understand the types of accidents that these vehicles will be involved in and how the mix will change over time with different levels of vehicle uptake and use patterns. Simulations of crash tests with L-category vehicles against larger vehicles, solid barriers and same size vehicles will be required to support the activity – guided by the results of the evolving accident scene, the behavioural studies and the technology development pathways..

6 Conclusions

Transport externalities are driving policy. An argument is made that smaller and lighter vehicles provide a possible response, but that issues around safety as well as cost are conspiring to hold back this sector. In seeking to understand the problems, the existing and proposed test procedures that target the smaller and lighter vehicles were analysed. This analysis revealed a number of concerns. First, is that these tests are less than suited to the smaller market – new vehicle sales around 2% of those achieved by M1 passenger cars in the European market meaning that application of the same test requirements would lead to increase in cost. Second, the L-category accident distribution and severity will likely be changed from that of the M1 passenger cars – calling into question the validity of applying a test procedure developed around addressing observed pattern pertaining to M1 passenger cars. Third, these tests would not result in the same performance of the L-category vehicle in real world collisions compared to M1 passenger vehicles even if they achieve the same performance in the actual test. These are valid concerns that will hold back this sector of the market and achieving a reduction in key transport externalities. In response a new test is proposed and discussed. It was identified that a new test must increase the impact energy – a mobile deformable barrier achieves this. It was identified that the test needs to align with the capabilities of this sector – the focus on structural performance achieves this. It was identified that costs must align with the lower sales volumes in this sector – removing a requirement for an anthropometric test device and the resulting costly fine tuning achieves this. The open questions were: how much energy to introduce; in reaching that energy, what should be the contribution of the mass and velocity of the mobile barrier; and what proportion of that energy should the barrier absorb? The target was to achieve a frontal force comparable to a mid-sized M1 passenger car. The barrier mass, velocity and barrier face are shown to be appropriate to achieving this objective. This test will deliver upon the requirement for improvement in compartment integrity; will align to the capabilities of the emerging L6e and L7e sector; and provide a cost effective solution that will enable a new mobility offer for consumers.

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